4 Heat-flux sensor calibration

4.1 Variable-Temperature Blackbody

The VTBB is a thermally insulated graphite tube cavity heated electrically. Figure 2 shows a schematic layout of the blackbody and the test arrangement for calibrating a typical heat-flux sensor. Direct resistance heating of the tube using large AC currents at low voltages provides for quick heating and cooling. The heated tube cavity diameter is 25 mm, and the heated section is 28.2 cm long with a center partition, 0.3 cm thick.

The water-cooled end caps of the heated tube connect directly to the heating electrodes. The design provides a sharp temperature gradient between the end cap and the graphite heater element, and a uniform temperature distribution along the cavity-length of the graphite tube. An optical pyrometer measures the blackbody temperature by sensing radiation from one end of the furnace. A Proportional-Integral-Derivative (PID) controller regulates the power supply to maintain the furnace temperature to within ± 0.1 K of the set value. The maximum recommended operating temperature for the blackbody is 2973 K.

With the standard extension installed and the sensor located 1.25 cm from the exit, the distance between the sensor and the end of the heated section will be 17.4 cm. However, the maximum flux-level at this location is limited. With a shorter-extension installed, the sensor location can be closer to the blackbody radiating-cavity resulting in higher flux-levels. At a distance of 1.25 cm from the exit, the maximum flux-level is approximately 50 kW/m^2. Away from the aperture, the irradiance decreases rapidly, and is about 10 kW/m^2 at a distance of 62.5 mm.

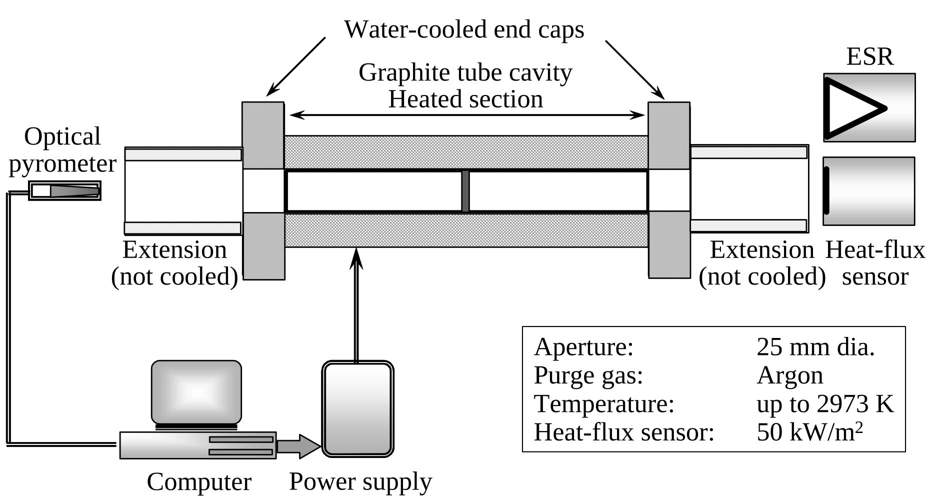

Figure 2. Schematic layout of the VTBB

4.2 Transfer Standard Radiometer

The ESR transfer standard is a water-cooled Kendall radiometer [4],[1] shown in Fig. 3. The ESR absorbs the incident radiant flux almost completely because of the blackened cavity walls and multiple reflections within the cavity. The equivalent electrical power, measured by the current through a precision resistor, required to produce the same cavity temperature rise as the radiant flux, is the power of the radiant flux. The maximum incident radiant power for the ESR is 4.2 W and the aperture area is 1 cm^2. The time constant (1/*e*) for a step change in irradiance is 6 s. For large changes in irradiance, it is necessary to allow about 60 s for stabilization before taking measurements [5]. The manufacturer stated uncertainty of this radiometer is 0.5 %, as determined by an experimental measurement of the Stefan-Boltzmann constant. Tables 1a and 1b give the radiometer and the control unit specification, respectively.

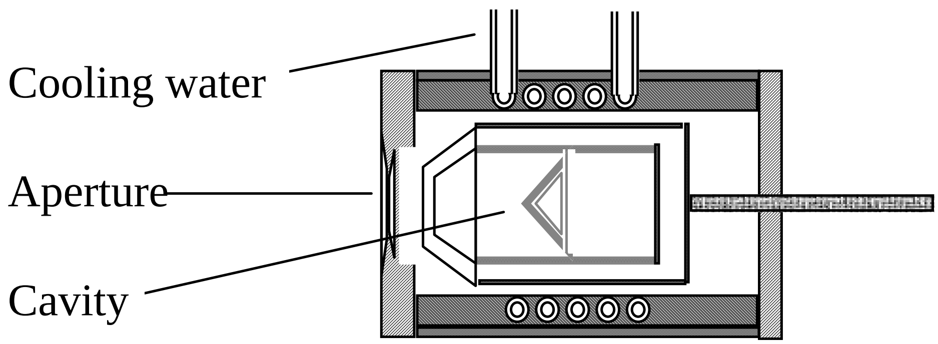

Figure 3. Transfer standard Kendall radiometer layout.

Table 1a. ESR transfer standard specifications

Type	Kendall MK-IV, S/N 47601
Range	0.04 kW/m^2 to 42 kW/m^2
Accuracy	± 0.5 % of reading ± 0.2 mW/cm^2
Time constant	6 s (1/*e*)
Sensitivity	> 10 mV/(W/cm^2)
View angle	No view limiting aperture
Calibration heater	230 W, 150 mA maximum
Outer surface coating	0.005 mm pure gold plate
Mounting	5 mm metric machine screw
Cabling	4 m long, Bendix PT06A-14-19P
Size	51 mm diameter, 76 mm long
Weight	0.9 kg

[1]manufactured by Technical Measurements Inc., La Cañada, CA. Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment are necessarily the best available for the purpose.

Table 1b. ESR transfer standard control unit specification

Kendall MK-I Radiometer Control Unit (Serial No. 17601)	
Accuracy	Absolute measurement uncertainty < ± 0.5 % full scale
Zero drift	< ± 0.1 % per month of full scale
Time constant	< 2 s (1/*e*)
Display	± 39 999 counts normal range
Output: Analog	± 10V, ± 5 mA
Output: Digital	Buffered, stored, parallel BCD
Size	43 cm wide, 14 cm high, 46 cm deep
Weight	10 kg

4.3 ESR Calibration

The self-calibration feature of the ESR facilitates absolute measurements of the incident irradiance within the stated experimental uncertainties. However, other uncertainties related to cavity heating and long-term drift make it desirable to characterize the radiometer independently by comparison to a QED with a high-power krypton laser [1]. The calibrations from three different sets of measurements of the ESR showed a high degree of linearity with a regression factor of 0.999. The calibration constant agreed to within 1 % between two tests conducted a year apart. From these tests, the relation between the corrected (E_c) and the indicated (E_i) ESR readings is obtained as [Appendix A]

$$E_c = 0.9855 E_i \ , \tag{5}$$

All of the calibrations performed with the VTBB use this relation to provide consistency and establish the long-term repeatability of the calibration technique. The uncertainty associated with the ESR calibration is of Type-B [7] in determining the total measurement uncertainty.

4.4 Reference Sensor Calibration

The heat-flux sensor calibration procedure is repeatable as demonstrated from periodic calibrations of a reference sensor. This reference sensor calibration, performed before calibrating a customer-supplied sensor, ensures that the long-term stability of the calibration procedure is monitored. The Schmidt-Boelter type reference sensor, shown in Fig. 4, works on the principle of axial one-dimensional heat flow. It measures the temperature difference across a thin, thermally insulating layer to determine the incident heat flux. Due to the axial flow of heat, the temperature distribution across the sensing surface is uniform. The maximum body temperature is limited to about 200 ^{o}C when the sensor is not water-cooled. For applications involving continuous use, the sensor body is water-cooled. Reference [6] gives a detailed description of Schmidt-Boelter sensor operation.

Table 2 lists the specifications of the Schmidt-Boelter reference sensor. The body diameter and length are 5 mm and 9 mm, respectively. The design heat-flux value of 110 kW/m^2 is representative of the calibration range of interest. A number of calibrations of this sensor performed over a period of time cover different locations from the blackbody aperture, and different blackbody temperature ranges. Figure 5 shows the results of the calibration for incident heat flux of up to 50 kW/m^2.

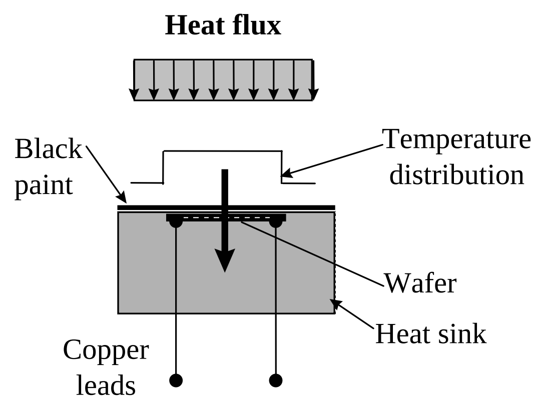

Figure 4. Schematic representation of a Schmidt-Boelter sensor

Table 2. Reference Schmidt-Boelter sensor specification

Type	Schmidt-Boelter
Manufacturer	Medtherm Corp.
Model	12-10-0.35-75-20841J
Serial Number	#94761
Design flux	110 kW/m^2
Body diameter	5 mm
Body length	9 mm
Thermocouple	Shielded copper wires
Body	not water-cooled

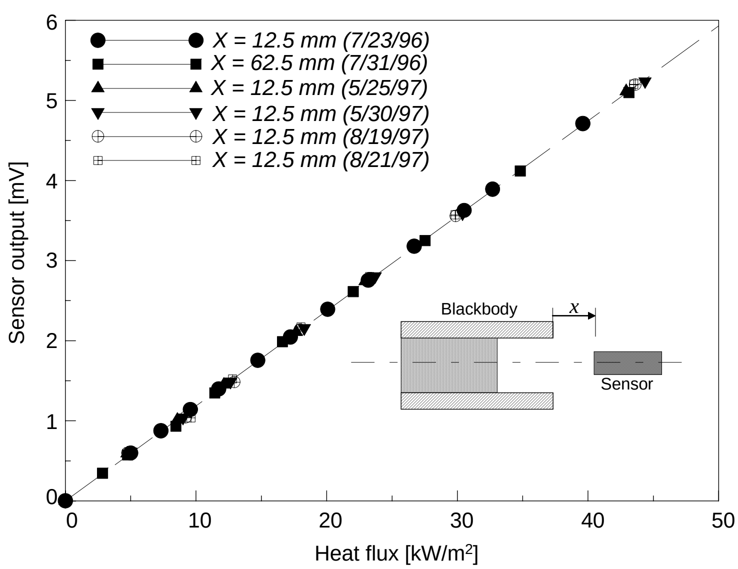

Figure 5. Typical calibration results on the reference sensor.

All of the calibrations show a linear response of the sensor, with regression factors close to unity. Table 3 summarizes the results of the sensor responsivity calculations from linear regression analysis of the measured data. The responsivity values from several calibrations agree to within ± 0.7 % of the mean value. The good repeatability of the data supports the long-term stability of the transfer standard ESR, the reference sensor, and validates the VTBB transfer calibration technique. The standard deviation of responsivity determined from these measurements is an additional source of uncertainty when determining the total uncertainty of other calibrated heat-flux sensors.

Table 3. Summary of linear regression results on the reference sensor

Schmidt-Boelter Sensor (NIST): #94761, 12-10-0.35-75-20841J					
Test		**Distance**	**Intercept**	**Responsivity**	
No.	**Date**	***x* mm**	**kW/m^2**	**mV/(kW/m^2)**	**Deviation %**
1	23-Jul-96	12.5	0.0018	0.1189	-0.18
2	31-Jul-96	62.5	-0.0687	0.1184	-0.59
3	25-Apr-97	12.5	0.0608	0.1190	-0.04
4	30-Apr-97	12.5	0.0186	0.1181	-0.83
5	19-Aug-97	12.5	0.0077	0.1191	0.06
6	21-Aug-97	12.5	0.0202	0.1197	0.50
7	9-Nov-97	12.5	0.1003	0.1200	0.76
8	11-Nov-97	140	-0.0186	0.1180	-0.92
9	2-Jun-98	12.5	0.1348	0.1189	-0.16
10	16-Jul-98	12.5	0.0318	0.1199	0.71
11	17-Jul-98	62.5	0.0053	0.1187	-0.31
12	27-May-98	12.5	0.1149	0.1188	-0.27
13	29-May-98	12.5	0.2526	0.1183	-0.62
14	9-Jul-00	12.5	-0.0644	0.1201	0.86
18	22-Jul-01	12.5	0.0300	0.1186	-0.38
19	16-Aug-01	12.5	0.0364	0.1183	-0.62
20	5-Nov-01	12.5	0.0374	0.1211	1.70
21	6-Nov-01	12.5	0.0472	0.1198	0.60
22	18-Aug-02	12.5	-0.0006	0.1187	-0.27
Arithmetic mean			**0.0393**	**0.1191**	**0.00**
Standard Deviation			**0.0732**	**0.0082**	**0.69**
Standard Error			**0.0168**	**0.0019**	**0.16**